A Complete Model of Low-scale GMSB

Part II

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Based on:
NC, Knapen, Shih & Zhao (1206.4086)

Recap

- Higgs@125 GeV in the MSSM requires large A-terms unless stops are extremely heavy.
- A challenge for GMSB (A-terms zero at messenger scale) unless messenger scale is quite high.
- Can introduce Higgs-messenger interactions to generate A-terms, but this generically induces an A-m_H^2 problem.
- The solution is MGM. Then one-loop soft masses-squared vanish to leading order in F/M; subleading contributions are negative.
- Gives rise to large A-terms, EWSB, and Higgs@125 GeV!

But what about...

μ and Bμ?!?

Generating μ and Bμ of the right order is one of the canonical problems of GMSB.

For nonzero λ_u and λ_d, the module for large A-terms actually *reintroduces* the μ-Bμ problem:

$$\mu = \frac{\lambda_u \lambda_d}{16\pi^2} \frac{F}{M} \qquad B_\mu = \frac{\lambda_u \lambda_d}{16\pi^2} \frac{F^2}{M^2} \qquad \mu^2 / B_\mu = \frac{\lambda_u \lambda_d}{16\pi^2} \quad !!!$$

(in general want $\mu^2 \sim B\mu \sim m^2$ for viable EWSB)

Can impose a $U(1)_X$ symmetry that sets λ_d=0, avoiding a μ-Bμ problem but thereby failing to explain the origin of μ and Bμ.

Whence μ and Bμ?

- Could assume an additional, distinct set of messenger interactions generates μ and Bμ (a la Giudice, Kim, & Rattazzi '07 or Craig, Knapen, & Shih 'TBD)
- Could introduce new dynamical scales peripherally related to F/M (a la Dine & Mason '07)
- Could ask for alternate forms of EWSB (a la Harnik, Kribs, Larson & Murayama '03 etc.)

Or we could just follow our noses. Perhaps the very interactions that generate large A-terms suggest a simple solution.

I.e., try the NMSSM. While NMSSM+GMSB has problems of its own, they are tidily solved by generalized Higgs-messenger interactions!

The second model: NMSSM

$$W \supset \lambda N H_u H_d - \frac{1}{3}\kappa N^3$$

NMSSM+GMSB

- Low-scale NMSSM+GMSB has problems akin to MSSM+GMSB: need two-loop negative m_N^2, one-loop A-terms, but GMSB doesn't generate these.
(de Gouvea, Friedland & Murayama '97; Morrissey & Pierce '08)

- But N-messenger couplings, suitably constructed, can do the job!
(Giudice & Rattazzi '97; Delgado, Giudice & Slavich '07)

- If we add this to our H_u/messenger couplings, we achieve a complete low-scale model of A-terms, μ and Bμ!

- A very simple, economical, and natural extension of the MSSM module. Gives you everything you need from GMSB in 2012.

Schematically

$$W \sim X\Phi\tilde{\Phi} + \lambda_u H_u \Phi\tilde{\Phi} + \lambda_N N\Phi\tilde{\Phi}$$

Challenges for NMSSM+GMSB

At low energies the (Z_3 symmetric) NMSSM entails $W \supset \lambda N H_u \cdot H_d - \frac{1}{3}\kappa N^3$

μ-term from vev of N: $\mu = \lambda \langle N \rangle$

Roughly speaking, this is fixed by $2\frac{\kappa^2}{\lambda^2}\mu^2 - \frac{\kappa}{\lambda}A_\kappa \mu + m_N^2 \sim \mathcal{O}(\lambda^2 v^2)$

Solutions given by

$$N_\pm \equiv \frac{A_\kappa \pm \sqrt{A_\kappa^2 - 8m_N^2}}{4\kappa}$$

$\Rightarrow$

Need one-loop A-terms and preferably negative m_N^2

Gauge mediation: no soup for you!

large tan beta further requires $m_N^2 = -A_\lambda(2A_\lambda - A_\kappa)$

Could try to approach this problem by adding N-messenger interactions, but generically one-loop A-terms also imply one-loop (positive) m_N^2

μ-$B\mu$ begets A-m_N^2

- Trying to solve the μ-$B\mu$ problem in NMSSM+GMSB gives rise to an A-m_N^2 problem to get the vacuum structure right.
- But we know how to solve an A-m_N^2 problem; it's identical to the A-m_H^2 problem!
- So just add N-messenger interactions with MGM messenger couplings; then the leading one-loop m_N^2 vanishes, leaving (negative) F/M-suppressed one-loop and two-loop contributions.
- This gives one-loop A-terms for the NMSSM potential and potentially satisfactory m_N^2

So the NMSSM part looks schematically like

$$W \supset X\Phi\tilde{\Phi} + \lambda_N N\Phi\tilde{\Phi}$$

As with most good ideas for SUSY model-building, Giudice (et al.) was here first ('97 and '07).

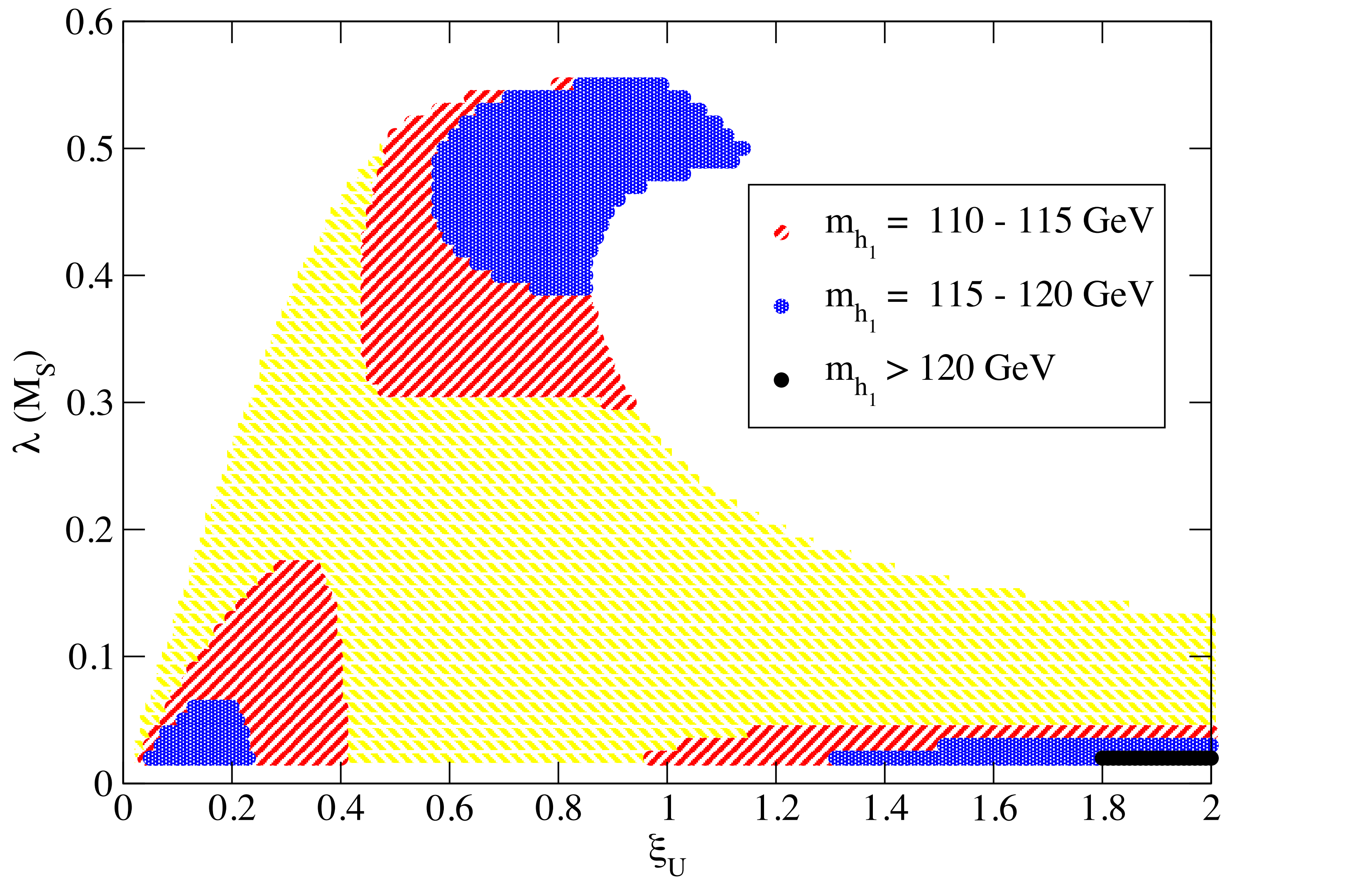


Figure 2: Mass of the lightest CP-even Higgs boson h_1 in the $\xi_U - \lambda(M_S)$ plane, for $M = 10^{13}$ GeV and $F/M = 1.72 \times 10^5$ GeV.

Delgado et al. investigated the NMSSM part of the model in '07. However, since they had zero A_t at the messenger scale, they again had to take very high messenger scales for the Higgs mass and vacuum. But even so, they could not really achieve m_h=125.

The model

$$W = X(\phi_i \cdot \tilde{\phi}_i + \varphi_i \cdot \tilde{\varphi}_i) + \lambda_u H_u \cdot (\phi_1 \cdot \tilde{\phi}_2 + \varphi_1 \cdot \tilde{\varphi}_2) + \lambda_N N \phi_i \cdot \tilde{\varphi}_i$$
$$+ \lambda N H_u \cdot H_d - \frac{1}{3}\kappa N^3 + y_t H_u \cdot Q \cdot U + \ldots$$

- i,j range over SU(3)xSU(2)xU(1) irreps.
- Most general superpotential consistent with
  - Z3: $\mathbb{Z}_3(X, \phi_i, \tilde{\phi}_i, \varphi_i, \tilde{\varphi}_i, H_u, H_d, N) = (0, 1, 2, 2, 1, 0, 2, 1)$
  - U(1)X : $q_X(X, \phi, \tilde{\phi}, \varphi, \tilde{\varphi}, H_u, H_d, N) = (1, 0, -1, -1, 0, 1, -1, 0)$
- Messenger irreps consistent with SU(5) GUT:
  - 5+5bar : $(\varphi_1, \varphi_2, \varphi_3), (\phi_1, \phi_2, \phi_3) = ((\mathbf{1}, \mathbf{1}, 0), (\mathbf{1}, \mathbf{2}, 1/2), (\mathbf{3}, \mathbf{1}, -1/3))$
  - 10+10bar: $(\varphi_1, \varphi_2, \varphi_3), (\phi_1, \phi_2, \phi_3) = ((\mathbf{3}, \mathbf{1}, 2/3),\ (\mathbf{3}, \mathbf{2}, 1/6),\ (\mathbf{1}, \mathbf{1}, 1))$

Need to double messengers and charge N under symmetries to avoid dangerous tadpoles from mixing with X

(note that we have chosen notation to manifest Z3 x U(1)X; $\phi \oplus \tilde{\phi}$ fill out GUT multiplets)

NMSSM+GMSB+A-terms

- Adding the H_u / messenger coupling to the model changes things qualitatively! Higgs and matter soft terms same as in David's talk, and now

$$A_\lambda \sim -\frac{N_m \alpha_{\lambda_u}}{4\pi}\Lambda - \frac{N_m \alpha_{\lambda_N}}{4\pi}\Lambda$$

$$A_\kappa \sim -\frac{3N_m \alpha_{\lambda_N}}{4\pi}\Lambda$$

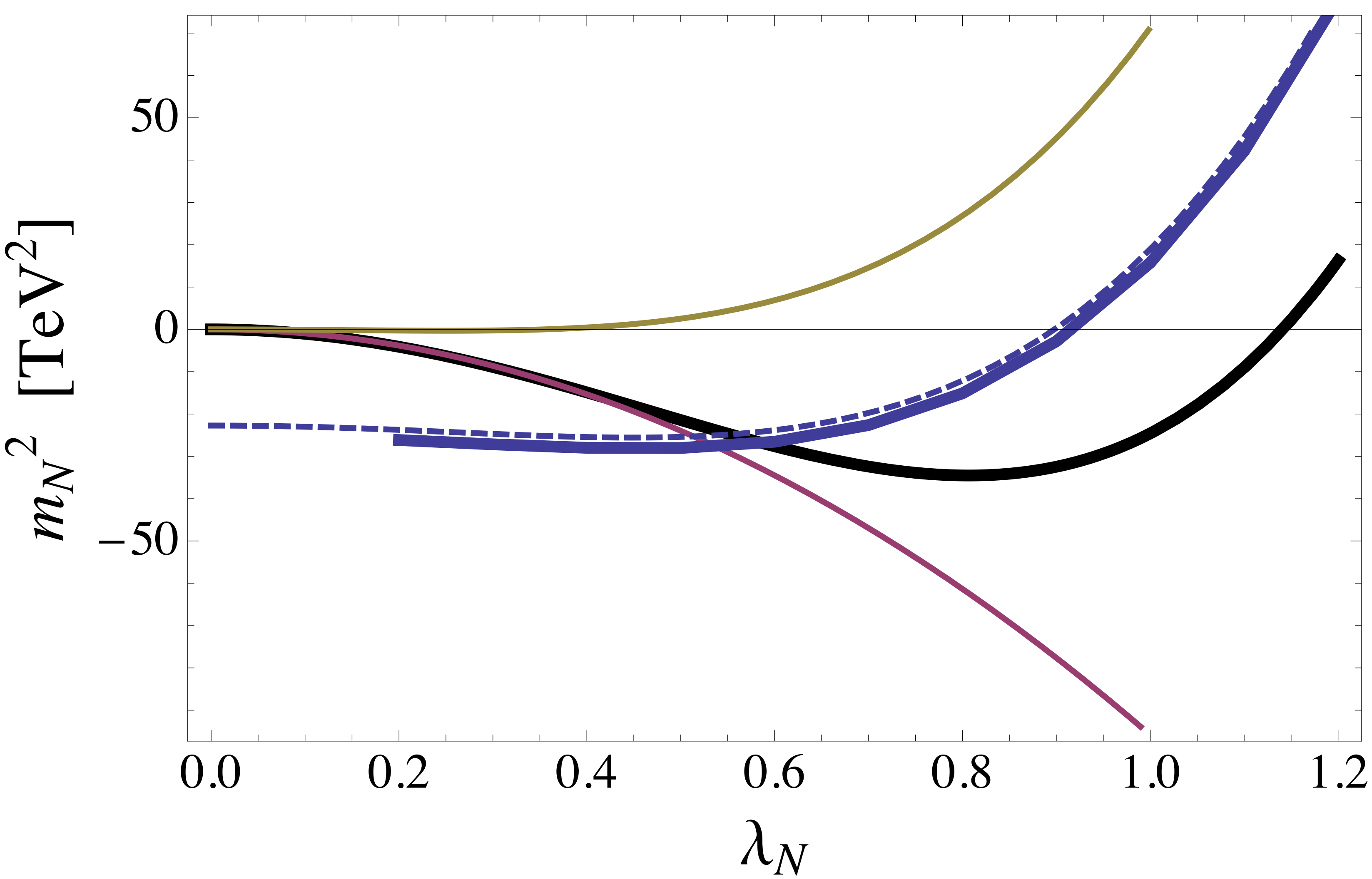
$$m_N^2 \sim \frac{N_m \alpha_{\lambda_N}}{4\pi}\left(-\left(\frac{\Lambda}{M}\right)^2 + \frac{N_m \alpha_{\lambda_N}}{4\pi} - \sum_{r=1}^{3}\frac{c_r \alpha_r}{4\pi}\right)\Lambda^2$$

- EWSB (at large tanbeta) requires $m_N^2 = -A_\lambda(2A_\lambda - A_\kappa)$

- So absent any cancellations, m_N^2 must be large and negative at the weak scale.

Rescuing low-scale GMSB again

- Again, negative one-loop m_N^2 saves us at low messenger scales!



blue: EWSB requirement

black: m_N^2 from model

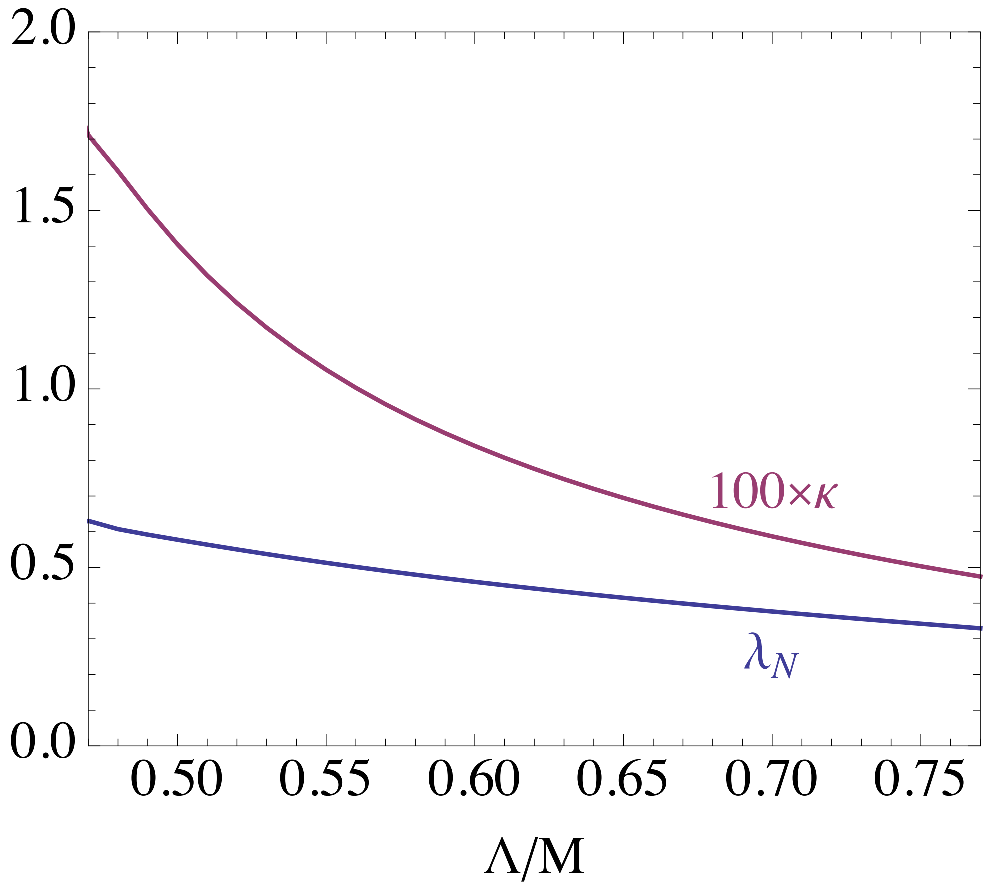
red: 1-loop contribution

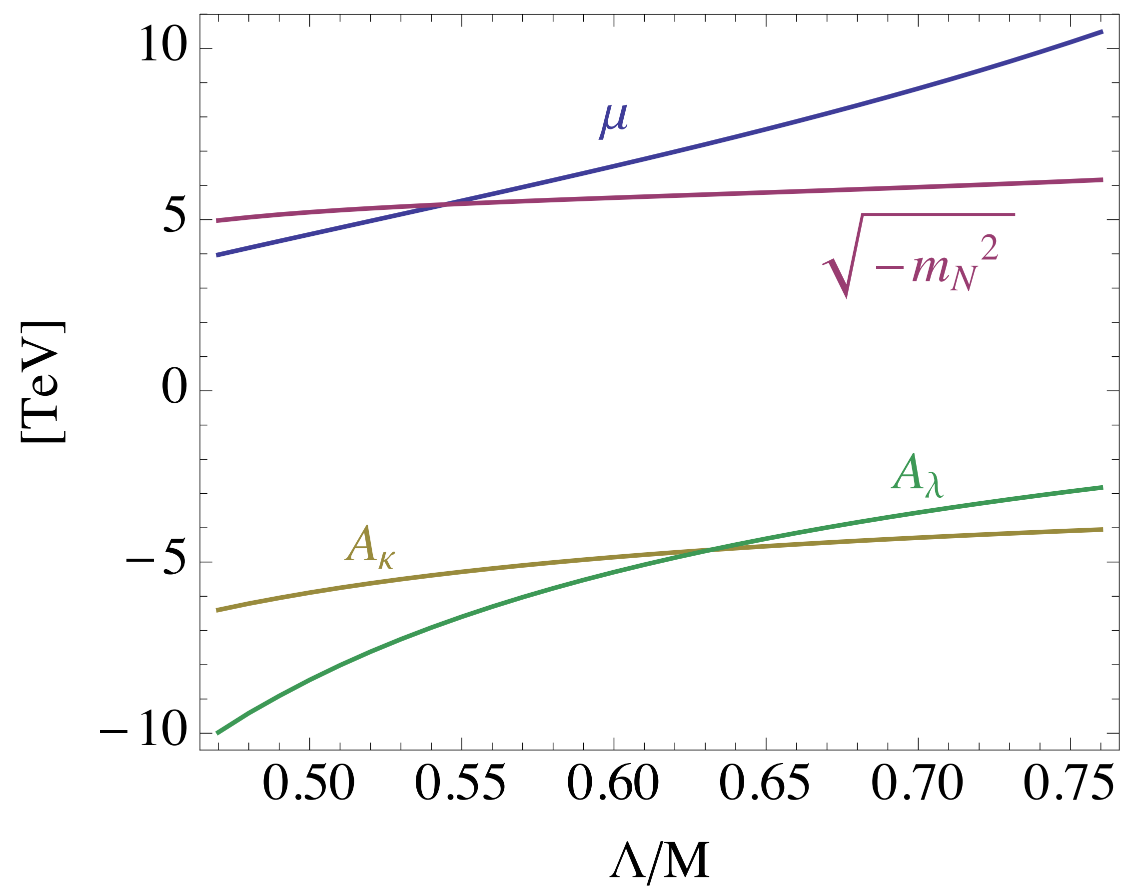
yellow: 2-loop contribution

(Λ = 110 TeV; M = 220 TeV; N_{mess} = 4; λ_u = 1.1; tanβ=10; λ, κ << 1)

Existence of a solution

- We find a consistent NMSSM solution exists in a window of moderate Λ/M





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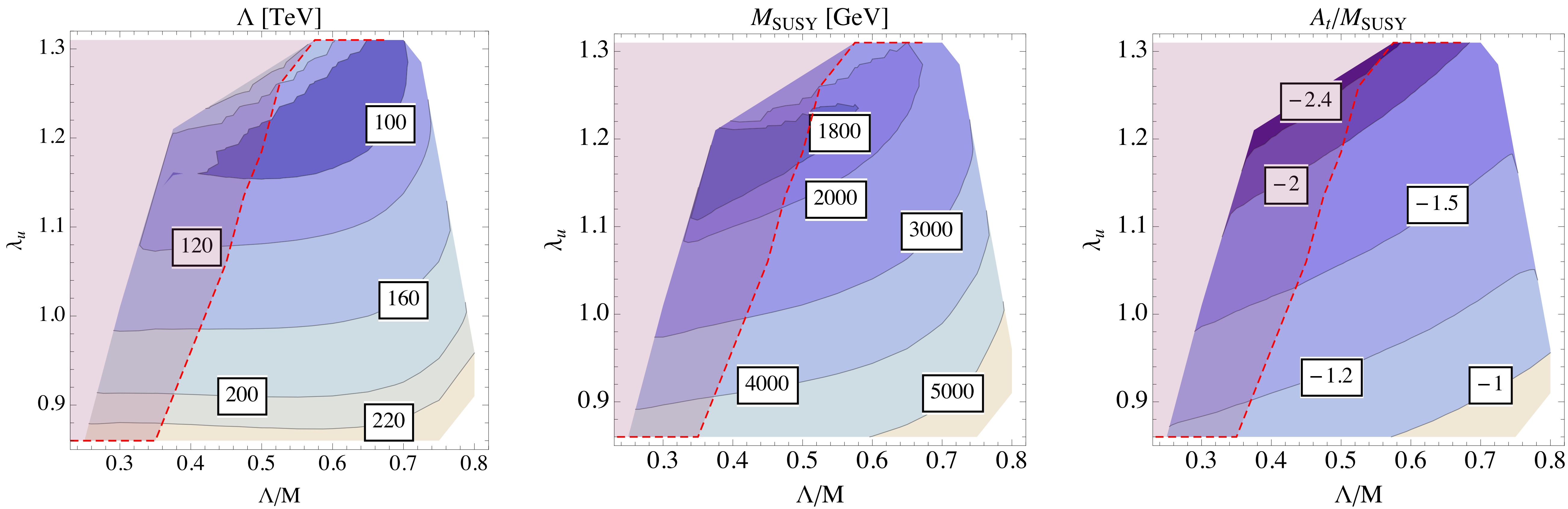
Plots (look familiar?)

The existence of a valid NMSSM solution places a constraint on the parameter space of the original model, but there is still plenty of room left.



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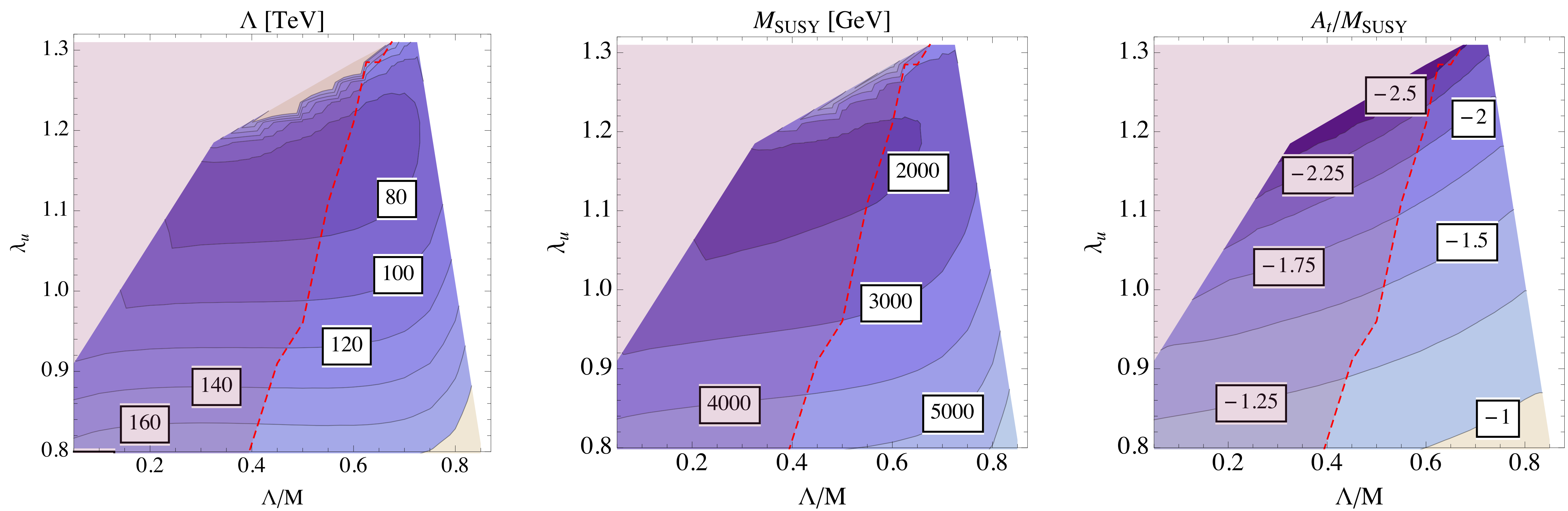

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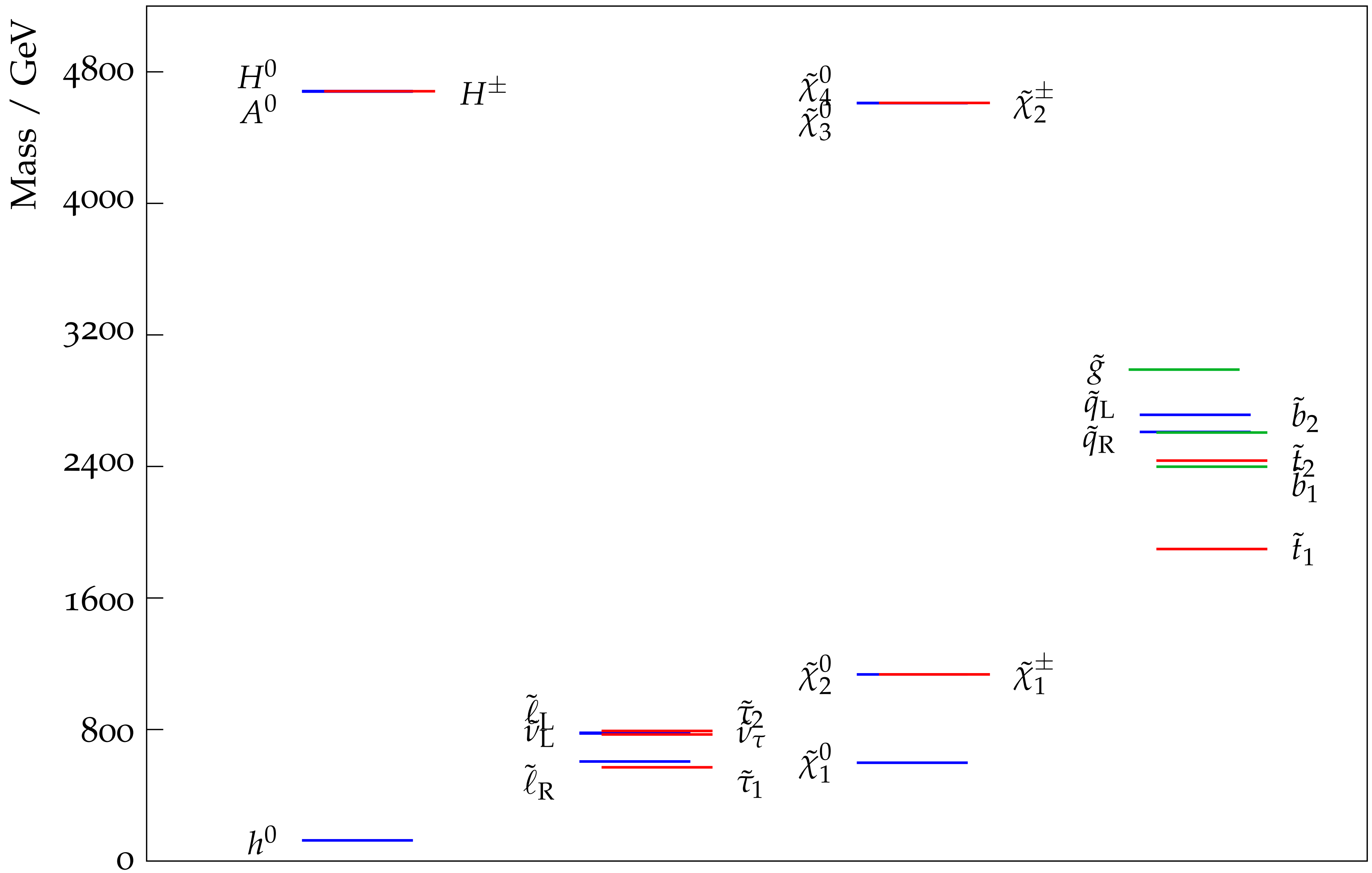
Pheno

A Sample Spectrum

NMSSM and MSSM spectra essentially identical; singlet is decoupled.



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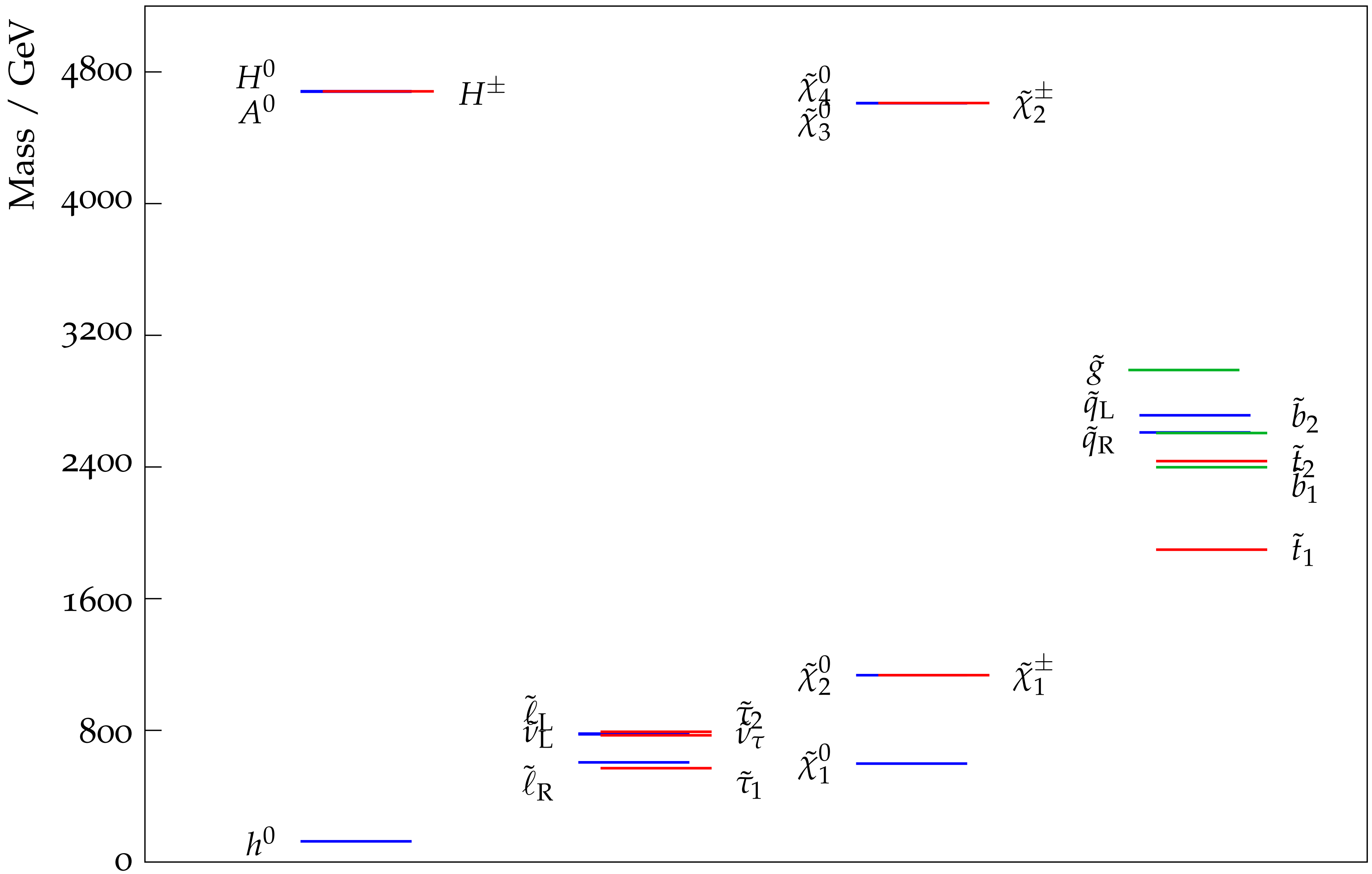

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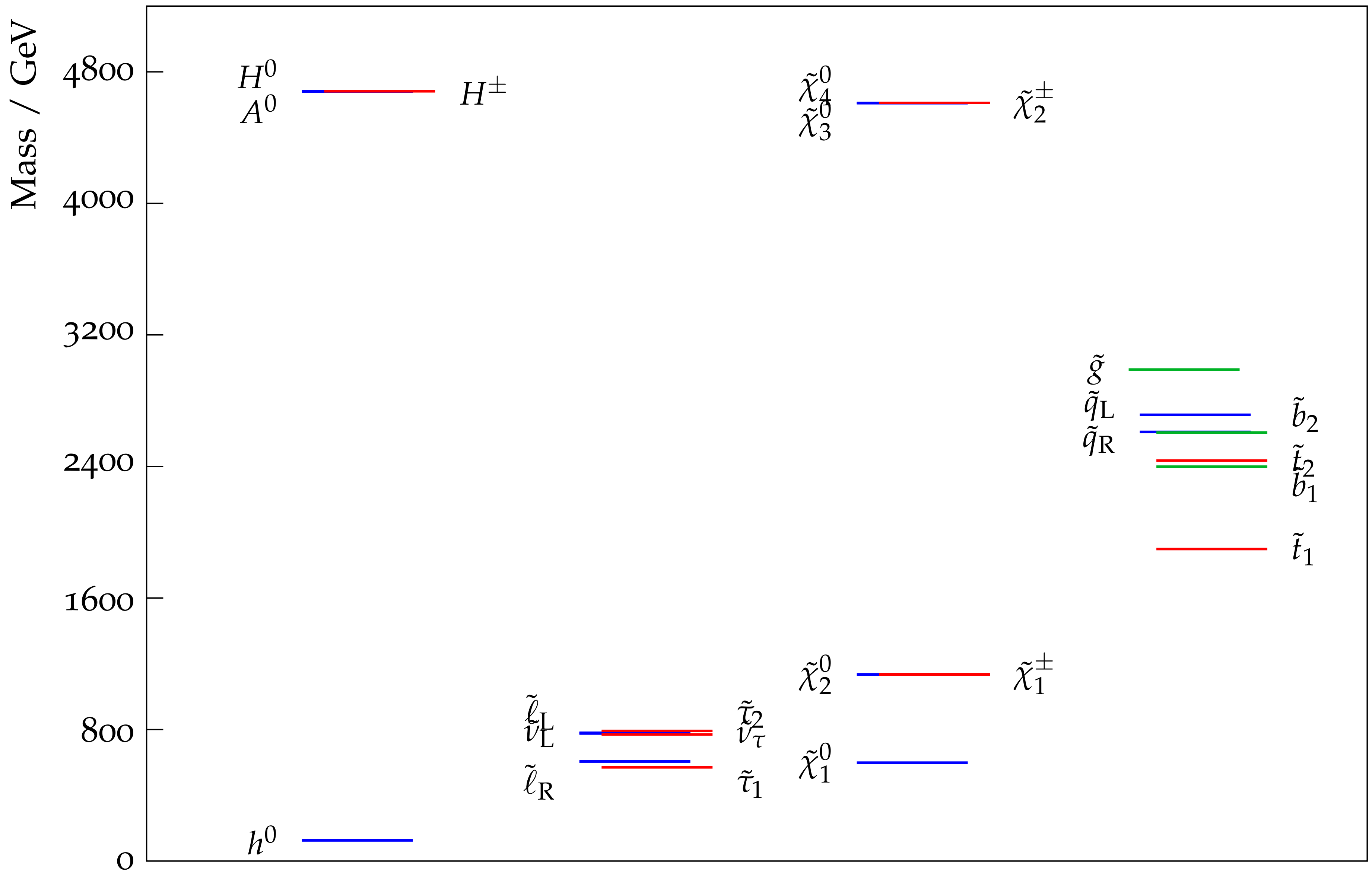

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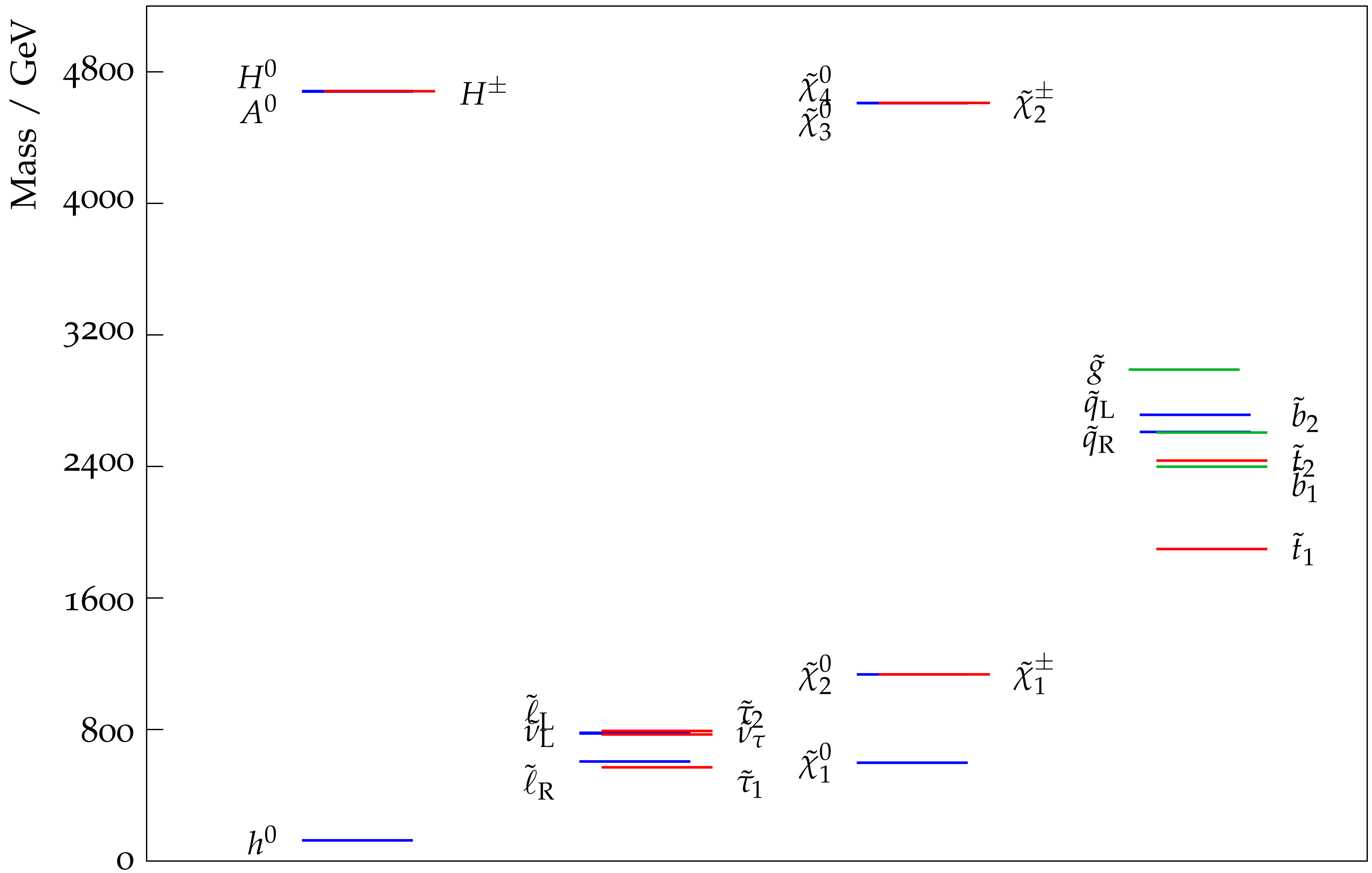

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Reassuringly, this spectrum (and most of our parameter space) is not yet ruled out at the LHC. This is guaranteed by requiring a solution to the A/mH^2 problem, which imposes MGM-like splittings in the soft spectrum and heavy colored fields.

Spectrum & Signals

- Stops are lightest colored sparticles due to negative contributions from Higgs-messenger couplings; split from other squarks by ~hundreds of GeV. Even so, stops typically above 1 TeV and gluinos above 2 TeV.

- Sleptons and electroweakinos below a TeV, with MGM splitting of wino and bino. Sleptons lighter than the wino.

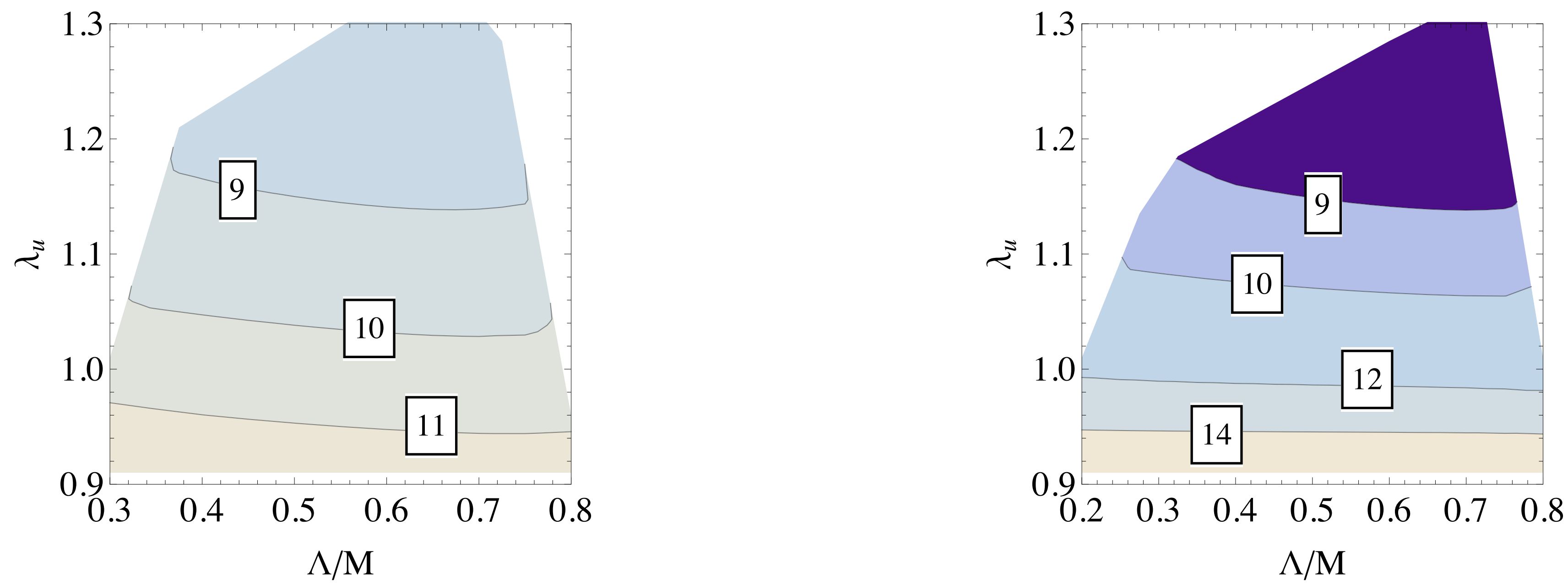
- NLSP invariably the stau (tiny parameter space for bino NLSP). Decays promptly in the detector since F is low.
  Multilepton searches are the key, but not yet constraining.

- Higgs sector is deep in the decoupling limit for both MSSM and NMSSM. Loop-level corrections negligible; predict Higgs couplings will be SM-like.

Models in the UV

Or: Where are the bodies buried?

No landau poles in the NMSSM sector since we're in the decoupling limit, using A-terms for the Higgs mass. Theory well-behaved up to the messenger scale. Above, however...



$$\beta_{\lambda_u} \sim \frac{\lambda_u}{16\pi^2}\left[(N_{mess}+3)\lambda_u^2 + 3y_t^2 + \ldots\right] \qquad (\mathbf{5}\oplus\overline{\mathbf{5}}\ \text{mess.})$$

$$\beta_{\lambda_u} \sim \frac{\lambda_u}{16\pi^2}\left[(3N_{mess}+3)\lambda_u^2 + 3y_t^2 - \frac{16}{3}g_3^2 + \ldots\right] \qquad (\mathbf{10}\oplus\overline{\mathbf{10}}\ \text{mess.})$$

5+5 messenger models have a landau pole in λ_u below GUT scale. 10+10 messengers can be safe. Either way, a signpost, not a killer: in dynamical SUSY breaking we expect new physics to enter at some scale.

Summary

- In these talks, we've reviewed the problems that Higgs@125 GeV places on the MSSM with gauge mediation.
- David presented a complete module of weakly-coupled messengers that solves these problems.
- I've shown how this module may be extended to a complete model that also addresses the $\mu/B\mu$ problem.
- The pieces of our model have been written down before (Kang et al; Giudice & Rattazzi; Delgado, Giudice & Slavich)
- But this is the first time they've been put together in a complete model of μ, $B\mu$ and large A-terms in the125 GeV Higgs era.

And the whole is more than the sum of its parts.

Summary

- Features of our model include:
  - Viability of low messenger scales
  - Preference for large messenger number
  - Stau NLSP, stops significantly lighter than the other squarks
  - Large negative $m_{H_u}^2$ (also m_N^2) already at the messenger scale (EWSB, but not radiative)
  - SM-like Higgs sector
- To solve the A-m_H^2 and A-m_N^2 problems, we're led back full-circle to Minimal Gauge Mediation. Is this a reason why we're not seeing anything yet at the LHC?

Future directions

- The model has a larger parameter space which we have not investigated. Can anything interesting happen here?
- We assumed $\lambda, \kappa << 1$ (MSSM decoupling limit) for simplicity. Are other regimes possible?
- Can one write down a weakly-coupled "existence proof" model of large A-terms + the full GGM parameter space?
- The messenger-Higgs couplings sometimes can have Landau poles before the GUT scale. But one can imagine these being remedied in many ways that point to...
- UV completions? Dynamical SUSY breaking?
- Cosmology? E.g., dark matter; Z_3 domain walls (NMSSM), etc.